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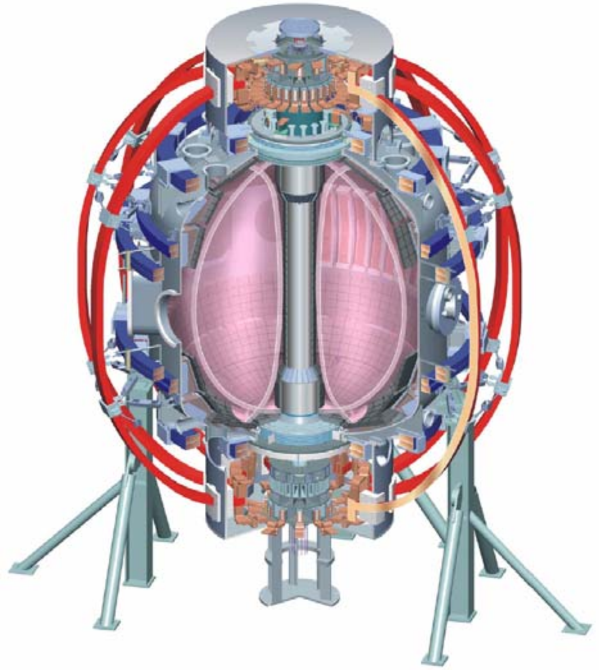
NSTX Research Plan – FY04-06

Contributing to Fusion Energy Science on a Broad Front



Martin Peng
Oak Ridge National Laboratory, UT-Battelle
@ Princeton Plasma Physics Laboratory

For the NSTX Team

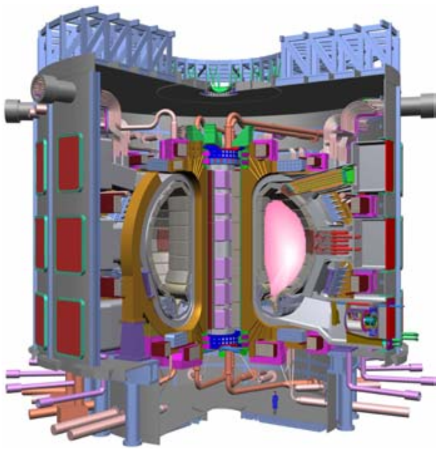
Budget Planning Meeting – FY 2006
Office of Fusion Energy Sciences

March 16 – 17, 2004
Germantown, Maryland

Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
NYU
ORNL
PPPL
PSI
SNL
UC Davis
UC Irvine
UCLA
UCSD
U Maryland
U New Mexico
U Rochester
U Washington
U Wisconsin
Culham Sci Ctr
Hiroshima U
HIST
Kyushu Tokai U
Niigata U
Tsukuba U
U Tokyo
JAERI
Ioffe Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
U Quebec

NSTX Team Contributes to Fusion Energy on a Broad Front Through Scientific Investigations

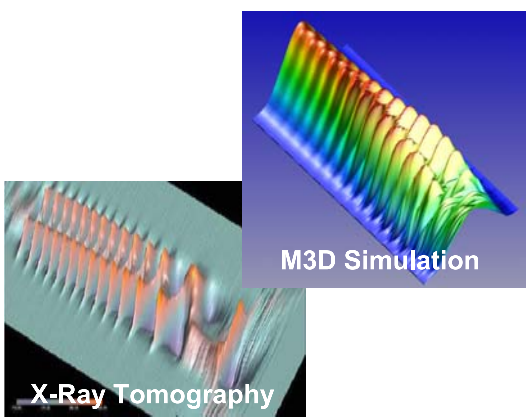
Burning Plasma (ITPA)



NSTX Team

Configuration Optimization

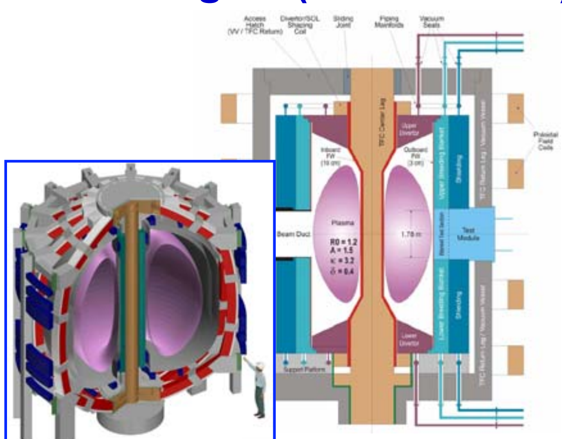
Fundamental Understanding



Scientific Topics

- **Turbulence**
- **Stability**
- **Waves & Energetic Particles**
- **Magnetic Flux Generation**
- **Boundary Physics**
- **Integration**

Materials, Components, Technologies (NSST & CTF)



NSTX Collaborators Directly Funded by DOE Make Crucial Contributions

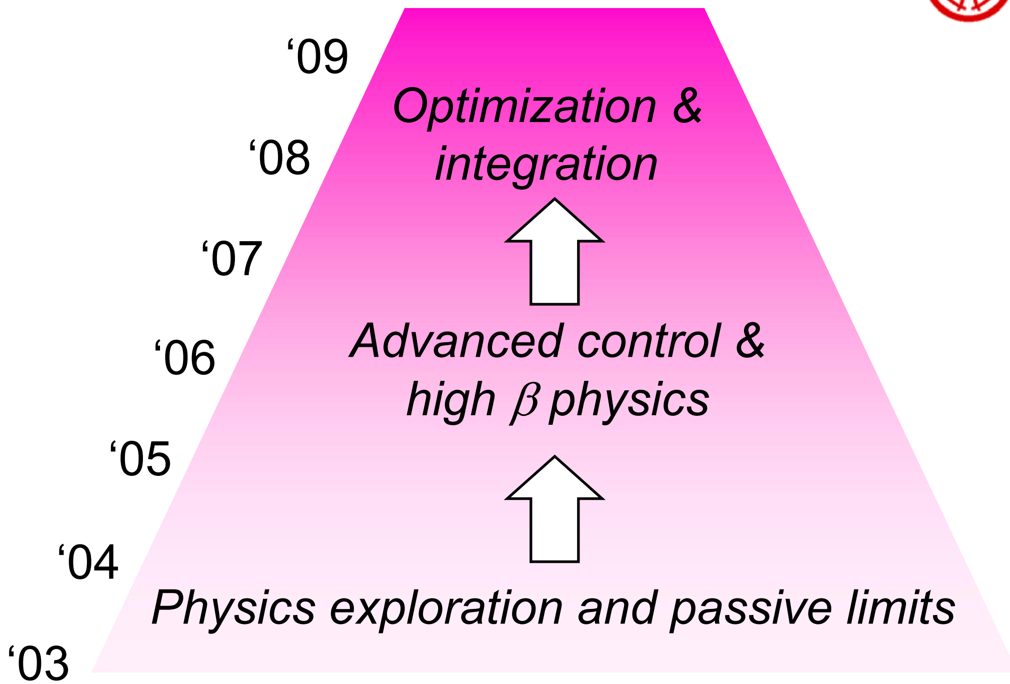
Institution	Research Topic
Columbia U	• MHD stability & mode control • Stellar x-ray spectroscopy
Comp-X	• CQL-3D kinetic modeling of RF heating & current drive
GA	• CHI equilibrium, RF physics • Plasma control • Poloidal field coil start-up
INEL	• Tile surface & dust analysis
Johns Hopkins U	• USXR tomography & diagnostics
LANL	• Visible and infrared imaging • Ultra-fast turbulence imaging • CHI plasma stability modeling
LLNL	• Edge SOL physics • Edge plasma turbulence • Stellar x-ray spectroscopy
Lodestar	• Edge plasma stability and turbulence
MIT	• ECW-EBW modeling • HHFW modeling

Institution	Research Topic
Nova Photonics	• MSE – CIF & LIF • Ultra-fast imaging (~10^6 /s) • Planar LIF
NYU	• Transport & RF modeling
ORNL	• HHFW & EBW physics & technology • Boundary and pedestal physics • RF & transport modeling
PSI	• Ultrafast imaging (~10^6 /s)
SNL	• Plasma-facing material • Material surface analysis
UC Davis	• FIReTIP n, B & fluctuations
UC Irvine	• Turbulence & fluctuations
UCLA	• Reflectometry & fluctuations
UCSD	• Fast probe, HHFW modeling • Far SOL turbulent transport
U Maryland	• Transport & turbulence simimulation
U New Mexico	• Fast ion-plasma interactions
U Washington	• CHI research
U Wisconsin	• NSTX neoclassical modeling

Funded by OFES NSTX, Theory, Technology, Diagnostic Innovations, SBIR, Plasma Science Programs.

Integration of High τ_E & High β in Solenoid-Free Plasmas for $\Delta t_{pulse} >> \tau_{skin}$ Is a Primary Goal of 5-Year Plan

NSTX



- 5-Year Plan favorably reviewed by DOE Panel
- Major new tool requirements were identified:
  - *Fluctuation diagnostics to* enable detailed comparison with theory in high β plasmas
  - *Enhanced shaping* to improve stability through simultaneous high κ and δ
  - *Mode control* to allow approach toward “with-wall” limits
  - *EBW off-axis* CD to keep q > 2 and stabilizes NTM & internal modes
  - *Particle control* to maintain moderate n_e for CD

FY04-06 Research Milestones Aim to Advance Control and High β Physics

NSTX

	FY04	FY05	FY06
Exp. Run-Weeks:	18	14	12
1) Transport & Turbulence: How does turbulence cause heat, particle & momentum losses?			
	(04-2) Measure low-k turbulence	(05-1) Measure high-k turbulence	
2) Macroscopic MHD Stability: What limits maximum plasma pressure & bootstrap current?			
		(05-2) Study plasmas near "with-wall" limit	
3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?			
	(04-3) Measure ΔJ from RF, NBI & ∇p	(05-3) Assess EBW H&CD requirements	
	(04-5) Characterize EBW emission, estimate H&CD		
4) Start-up, Ramp-up and Sustainment: How is plasma magnetic flux generated?			
	(04-4) Test current initiation		(06-1) Test solenoid-free ramp-up to high current
5) Boundary Physics: How to interface fusion plasmas to surrounding materials?			
			(06-2) Characterize edge of H-mode plasmas
6) Integration: How much external control vs. self-organization is needed?			
	(04-1) Assess high τ_E & high β_T H-mode for >> τ_E	(05-4) Assess combined RF & NBI effectiveness	(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$

FY04-06 Research Milestones under Incremental Plan Will Enable Timely Achievement of the "5-Year" Goal

	FY04	FY05	FY06
Exp. Run-Weeks:	18	14 (7)	12 (6) ← Incr. Request

1) Transport & Turbulence: How does turbulence cause heat, particle & momentum losses?

	FY04	FY05	FY06
	(04-2) Measure low-k turbulence	(05-1) Measure hi-k turbulence	

2) Macroscopic MHD Stability: What limits maximum plasma pressure & bootstrap current?

	FY04	FY05	FY06
		(05-2) Study plasmas near "with-wall" limit	(06-4-Incr) Identify tearing modes & onset conditions

3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?

	FY04	FY05	FY06
	(04-3) Measure ΔJ from RF, NBI & ∇p	(05-3) Assess EBW H&CD requirements	
	(04-5) Characterize EBW emission, est. H&CD		

4) Start-up, Ramp-up and Sustainment: How is plasma magnetic flux generated?

	FY04	FY05	FY06
	(04-4) Test current initiation		(06-1) Test solenoid-free ramp-up to high current

5) Boundary Physics: How to interface fusion plasmas to surrounding materials?

	FY04	FY05	FY06
		(05-5-Incr) Characterize edge of H-mode plasmas	(06-2-Incr)Assess long-pulse heat & particle control requirements

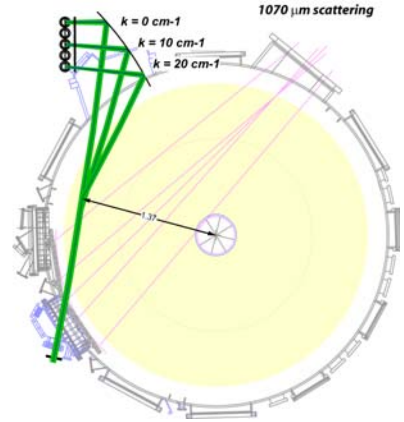
6) Integration: How much external control vs. self-organization is needed?

	FY04	FY05	FY06
	(04-1) Assess hi τ_E & hi β_T H-mode for >> τ_E	(05-4) Assess combined RF & NBI effectiveness	(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$

Transport Studies Aim to Characterize Low & High k Turbulence at High β, Low A & Strong Flow

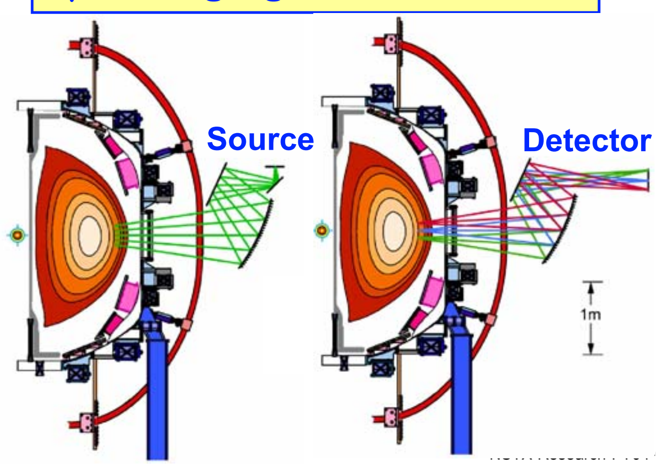
FY04	FY05	FY06
1) Turbulence: How does turbulence cause heat, particle & momentum losses?		
(04-2) Measure low-k turbulence	**(05-1) Measure high-k turbulence**	

- **Opportunity: different transport conditions exist where**
  - $\chi_e \gg \chi_i$: helpful to high-k turbulence studies
  - $\chi_i \sim \chi_i^{NC}$: stable low-k turbulence
  - $\chi_\phi < \chi_i$: different from TFTR
  - Effects of large β, ρ*, V_ϕ (~0.3$V_{Alfvén}$), V_ϕ'; L & H-mode
- **Tools, measurements and theory comparison**
  - FY04: μw reflectometers, FIR interferometer
  - FY05: high-k μw scattering at 300 GHz
  - FY07: μw imaging reflectometer (delayed from FY06)
  - FULL, NLGS2, GTC, GYRO, TRANSP, NCLASS, …
- **ITPA: joint experiments with DIII-D, C-Mod, MAST**
  - Comparisons of A, β effects & ITB physics
  - ELMy H-mode with $T_e \sim T_i$ & low input momentum
  - Identity and Similarity tests of H-mode transitions & pedestal physics



High-k μw scattering system

μw Imaging Reflectometer



MHD Studies Aim to Understand the Physics of β Limiting Modes to Enable Very High β

NSTX

FY04	FY05	FY06

2) Stability: What limit maximum plasma pressure & bootstrap current?

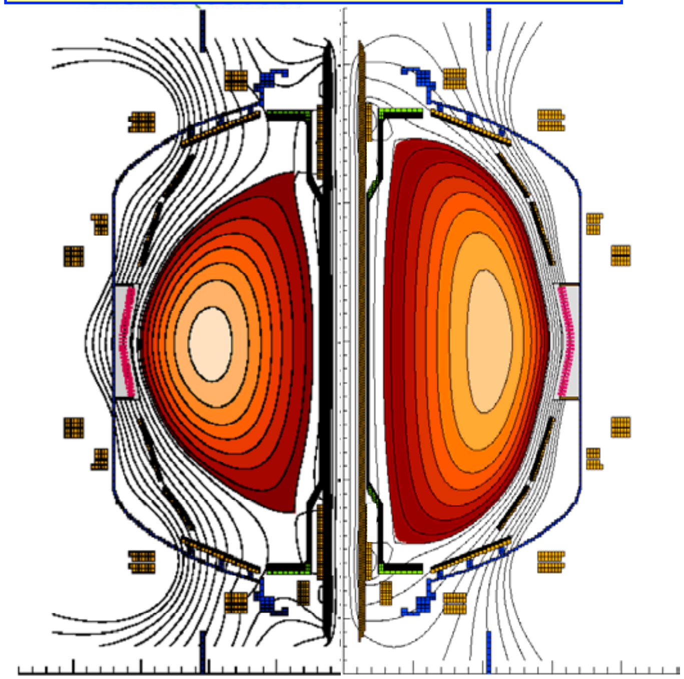
(05-2) Study plasmas near "with-wall" limit

(06-4-Incr) Identify tearing modes & onset conditions

- **Opportunity: $\beta_0 \sim 1$, $V_{Alfven} \sim V_{Thermal} \sim 3V_{\phi}$, $V_{\phi}' \sim \gamma_{MHD}$**
  - Reached β_T = 35% at κ = 2, δ = 0.8
  - Study RWM, internal mode rotation damping physics
  - Can reach κ=2.55, δ=0.8 with PF1A modification
- **Tools, measurements, control & theory comparison**
  - FY04: install ex-vessel control coils; test rotation damping via error field reduction
  - FY05: commission & apply active field & RWM control
  - FY06-Incr: identify pressure-limiting tearing mode conditions
  - EFIT-V_{ϕ}, VALEN, MARS, M3D, GATO, PEST, DCON
- **ITPA: DIII-D, MAST, AUG, JET, JT-60U, C-Mod**
  - Compare RWM varying $V_{Alfvén}/V_{Thermal}$; compare NTM varying A; error field sideband effects
- **ICC: relevant to MST, SSPX, FRC high β stability**

Calculated Equilibria:

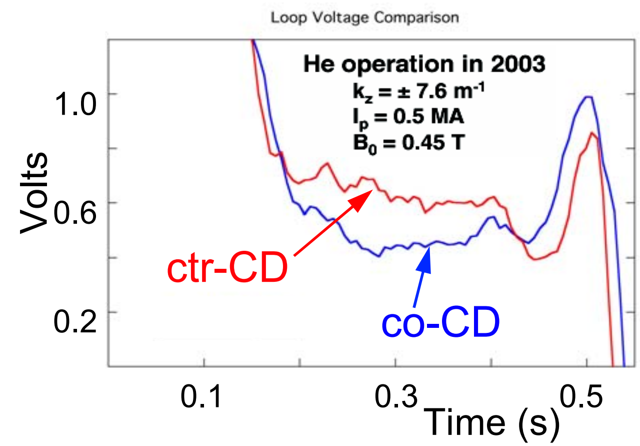
κ:	2.0	2.55
PF1A:	Present	Modified

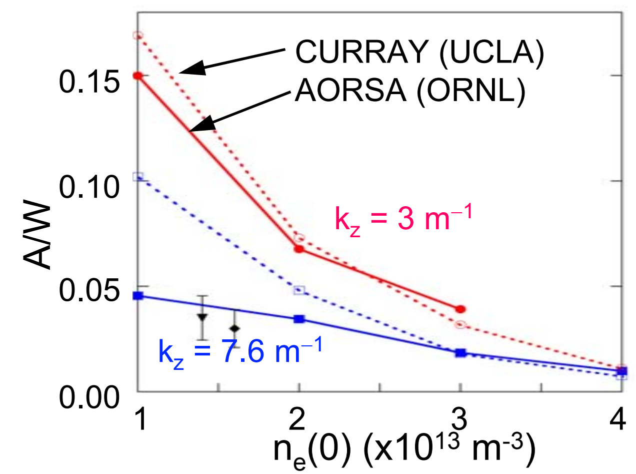


HHFW Aims to Test Current Drive in FY04 and Prepares for J_{NI} = 100% Demonstration in FY06

FY04	FY05	FY06
3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?		
(04-3) Measure ΔJ from RF, NBI & ∇p	**(05-4) Assess combined RF & NBI effectiveness**	**(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$**

- **Opportunity: HHFW in overdense plasmas (ST, RFP)**
  - Observed effective electron heating
  - Observed CD @ $k_z = 7.6\ m^{-1}$
  - Modeling indicates $3\ m^{-1}$ should drive more current
  - Assess fast & thermal ion coupling
- **Tools, measurements & theory comparison**
  - FY04: commission multi-chord MSE CIF
  - CHERS & edge spectroscopy resolve E_r effect
  - Tangential polarimetry & X-Ray imaging contribute
  - Prepare for RF+NBI (FY05) & J_{NI} = 100% evaluation (FY06)
  - RF modeling, 1D & full-wave comparison, scenario simulation: CURRAY, HPRT, TORIC, AORSA, METS
- **ICC applications**
  - MST, Pegasus, CDX-U (LTX)





EBW Studies Will Establish Physics Basis in FY04-05 for Design of High-Power System in FY06

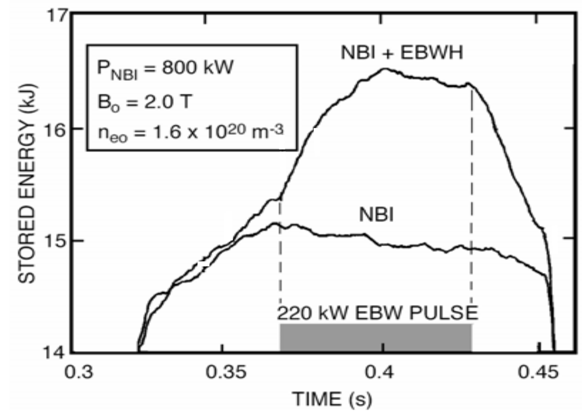
FY04	FY05	FY06

3) Wave-Particle Interaction: How do electromagnetic waves interact with plasma?

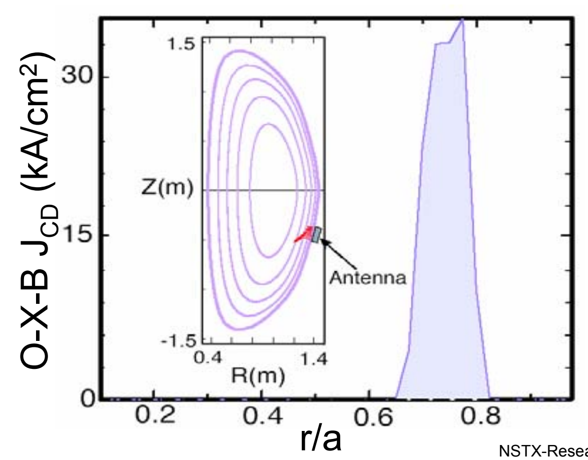
(04-5) Characterize EBW emission, estimate H&CD	**(05-3) Assess EBW H&CD requirements**	

- **Opportunity: EBW in overdense plasmas (ST, RFP)**
  - Measured thermal emission in CDX-U, NSTX, MAST
  - Successful H&CD on W-7AS, COMPASS-D
  - Predicted large & localized H&CD profiles in NSTX
- **Tools, measurements, theory comparison, design**
  - FY04: X-B & O-X-B emission studies
  - FY05: collaborative H&CD tests on MAST @ 28 & 60 GHz and 200 & 700 kW level, respectively
  - FY05: EBW test on DIII-D, pending analysis results
  - GENRAY, CQL3D (NSTX); OPTPOL, GLOSI (MAST)
  - FY06: model H&CD scenarios and begin launcher design
- **ICC applications**
  - Pegasus, TST-2, MST, SSPX
  - New ST experiments: LATE (Japan), SUNIST (PRC)

W7-AS: O-X-B Data @ 140GHz



NSTX: 135kA @ 28GHz, 3MW, 40% β_T



Solenoid-Free Start-up Will Be Tested Extensively in FY04-06 Towards Future ST and AT Devices

NSTX

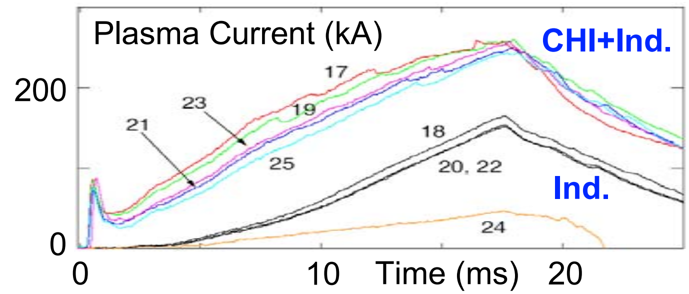
FY04	FY05	FY06

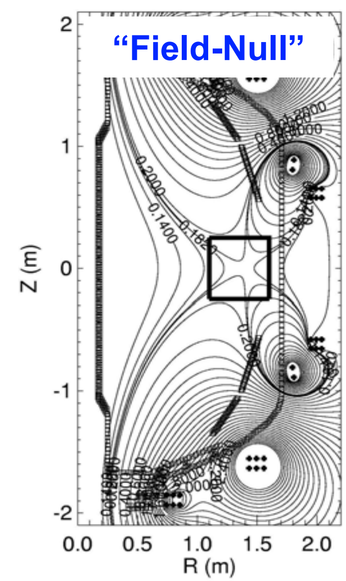
4) Start-up, Ramp-up and Sustainment: How is plasma magnetic flux generated?

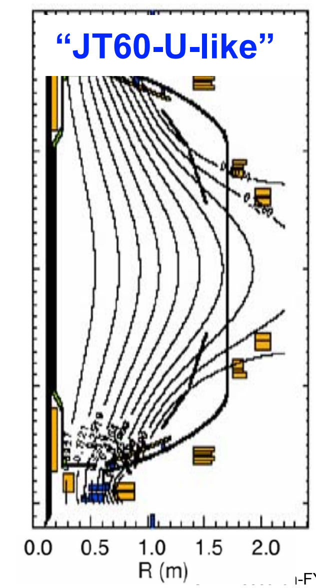
FY04	FY05	FY06
(04-4) Test current initiation		**(06-1) Test solenoid-free ramp-up to high current**

- **Opportunity: solenoid-free startup shows promise**
  - **CHI:** 100kA on HIT-II; 390kA on NSTX
  - **Merging-compression:** 500 kA on MAST
  - **ECH, LHCD & NBI:** 200→600 kA on JT60-U
  - **ECH:** 20 kA, 8 kA on DIII-D, TST-2
  - EBW solenoid-free startup to high β_p
- **Tools, measurements & theory comparison**
  - FY04: Capture CHI plasma by induction, HHFW
  - FY04: Test outer PF-coil start-up scenarios, using ECH pre-ionization and HHFW heating
  - Collaborative tests with MAST, DIII-D, TST-2
  - FY06: test start-up scenarios to high current
  - TSC, DINA (DIII-D), EFIT-J_{SOL}, LRDIAG
- **ITPA & ICC applications**
  - Save V-s on ITER? ⇒ increase inductive I_p, t_{pulse}
  - Pegasus, TST-2, LATE, SUNIST

HIT-II captured CHI plasma by induction





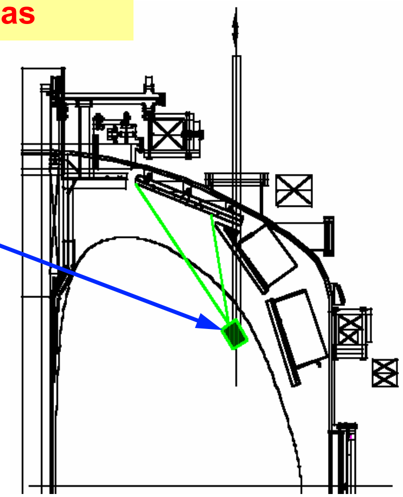


Boundary Physics Studies Aim to Develop and Test Solutions for Long-Pulse High-Performance Plasmas

FY04	FY05	FY06
5) Boundary Physics: How to interface fusion plasmas to surrounding materials?		**(06-2) Characterize edge of H-mode plasmas**

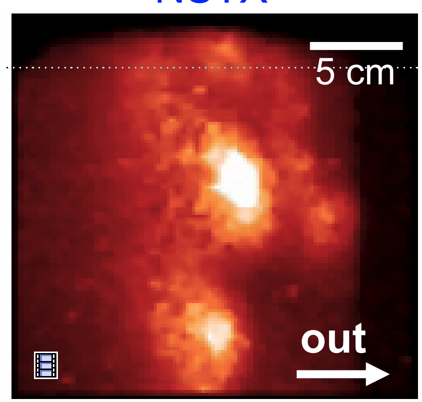
- **Opportunity: $B_p/B_T \sim 1 \Rightarrow$ >10 SOL expansion, large B_{in}/B_{out} ratio & ρ^***
  - Divertor footprint larger than R-ratio $\Rightarrow$ favorable SOL at low A and high δ
  - Li: Cost-effective way to control recycling
- **Tools, measurements & theory comparison**
  - FY04: lithium pellets, supersonic gas jet, fast imaging
  - FY05: lithium coating; more edge TS points
  - FY06: fast IR camera; poloidal CHERS
  - Study ELM & “blob” fluxes
  - **Decision: cryo-pump or lithium module**
- **ITPA: DIII-D, C-Mod, AUG comparisons**
  - H-mode, pedestal, edge turbulence
  - Type-I ELM energy flux, $\chi_\perp$, n_{sep}, SOL profiles

E-beam Deposition System

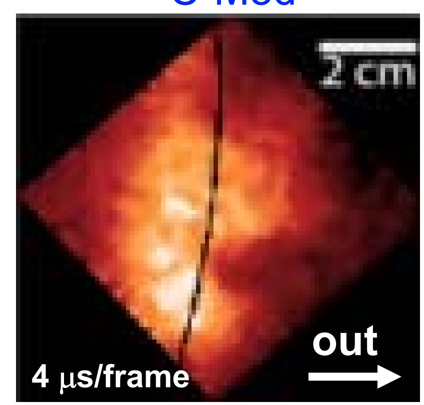


Edge Turbulence

NSTX



C-Mod



Integration Studies Will Assess Compatibility of Requirements for Stability, Transport, Heating & Current Drive

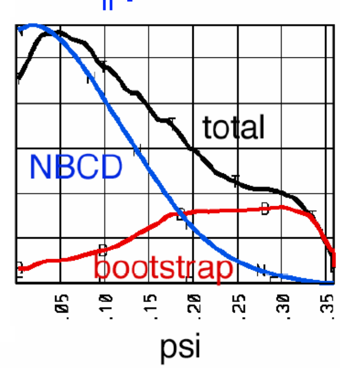
NSTX

	FY04	FY05	FY06
6) Integration: How much external control vs. self-organization is needed?	**(04-1) Assess high τ_E & high β_T H-mode for >> τ_E**	**(05-4) Assess combined RF & NBI effectiveness**	**(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$**

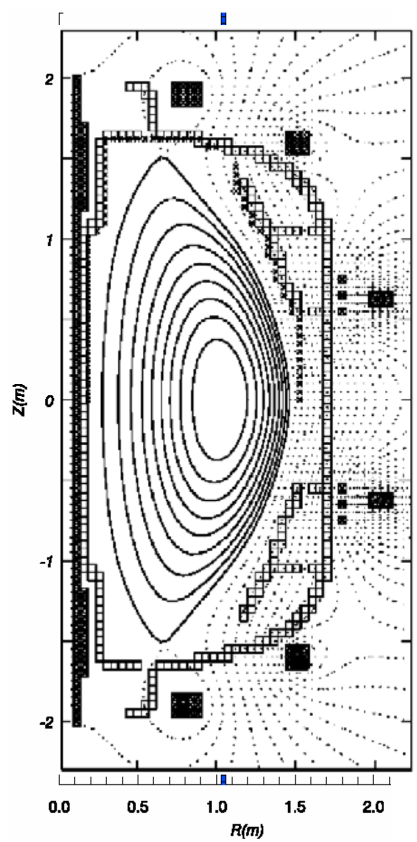
- **Opportunity: High β, low A & low B change the balance of external & internal influences**
  - FY04: assess high τ_E at high β
  - FY05: assess combined RF & NBI effectiveness in H&CD
  - FY06: evaluate conditions for 100% non-inductive operation using **NBI & HHFW only**
- **Tools, modeling & scenario simulation**
  - Guide experiment with extensive modeling & scenario simulation
  - Decisions: multi-MW EBW (FY05); active particle control (FY06)
- **ITPA, future ST & ICC application**
  - ITER hybrid scenario
  - Larger ST physics requirements

I_p = 0.8 MA
κ = 2.6; δ = 0.38
P_{NBI} = 6 MW
P_{HHFW} = 6 MW
P_{EBW} = 0
$\langle n_e \rangle = 3\text{x}10^{19}\text{m}^{-3}$
H_{98y2} = 1.2
β_T = 19%; β_N = 6.8
Stable n = 1 & ∞

$J_{||}$ profiles



TSC: NBI+HHFW



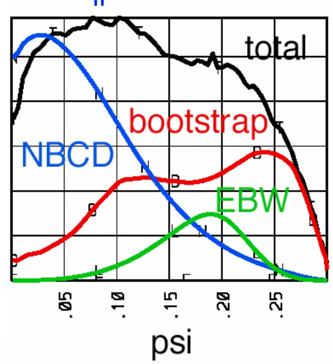
"Five-Year" Plan Goal Drives Major NSTX Decisions on EBW and Particle Control Capabilities

FY04	FY05	FY06
6) Integration: How much external control vs. self-organization is needed?		
(04-1) Assess high τ_E & high β_T H-mode for >> τ_E	**(05-4) Assess combined RF & NBI effectiveness**	**(06-3) Evaluate J_{NI} ~ 100% for $\geq \tau_{skin}$**

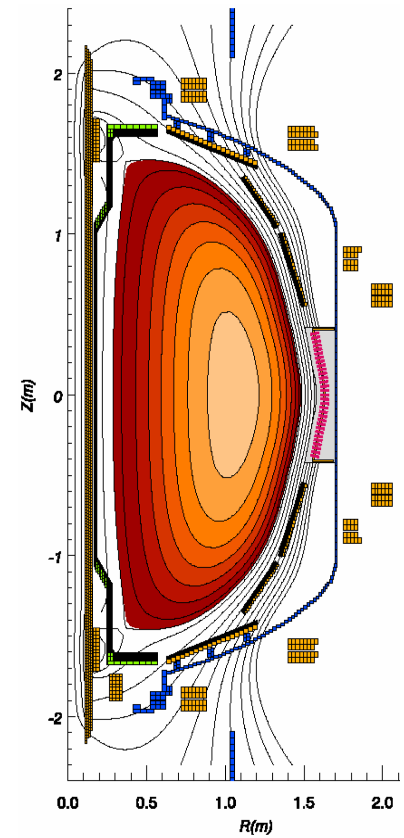
- **Opportunity: High β, low A & low B change the balance of external & internal influences**
  - FY04: assess high τ_E at high β
  - FY05: assess combined RF & NBI effectiveness in H&CD
  - FY06: evaluate conditions for 100% non-inductive operation using NBI & HHFW only
- **Tools, modeling & scenario simulation**
  - Guide experiment with extensive modeling & scenario simulation
  - **Decisions: multi-MW EBW (FY05); active particle control (FY06)**
- **ITPA, future ST & ICC application**
  - ITER hybrid scenario
  - Larger ST physics requirements

I_p = 1 MA
κ = 2.55; δ = 0.8
P_{NBI} = 4 MW
P_{HHFW} = 3 MW
P_{EBW} = 3 MW
$\langle n_e \rangle$ = 2.7x10^{19}m^{-3}
H_{98y2} = 1.5
β_T = 41%; β_N = 8.9
Stable n = 1 & ∞

$J_{||}$ profiles



TSC: High-Performance Sustained Plasma

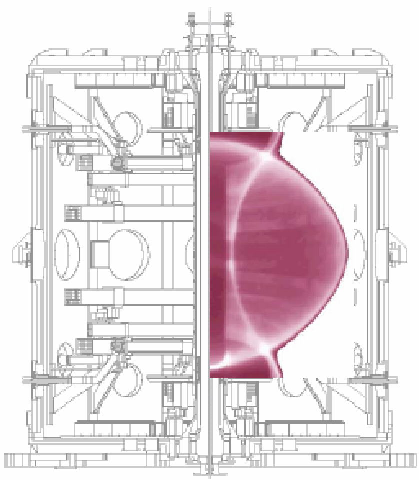


Worldwide NSTX Collaborations are Enhancing Contributions to ITPA-ITER

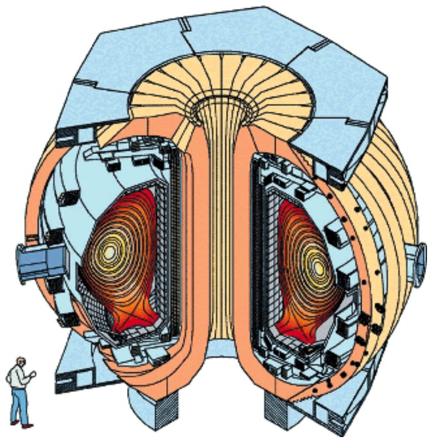
NSTX

- **Extensive collaboration with MAST**
  - NBI H-mode, ITB, τ_E scaling
  - EBW H&CD, start-up (28, 60 GHz)
  - Fueling, SOL pedestal studies
  - Energetic particle characterization
- **Strong participation in ITPA**
  - **DIII-D, C-Mod**: RWM, Fast ion MHD, pedestal, core confinement, edge turbulence, x-ray crystal spectrometry, EBW
  - **A and β effects**: H-mode, ITB, ELM's & pedestal, SOL, RWM, NTM
- **Exploratory ST experiments**
  - **Pegasus**: Extreme low A, EBW
  - **CDX-U/LTX**: Li-plasma
  - **TST-2, LATE, SUNIST**: RF start-up, H&CD
  - **TS-3,4**: FRC-like β~1 ST plasmas
  - **HIT-II/HIT-SI, HIST**: CHI physics

MAST (U.K.)

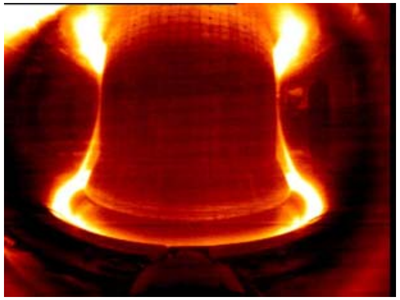


DIII-D (U.S.)



Pegasus (U.S.)

C-Mod (U.S.)

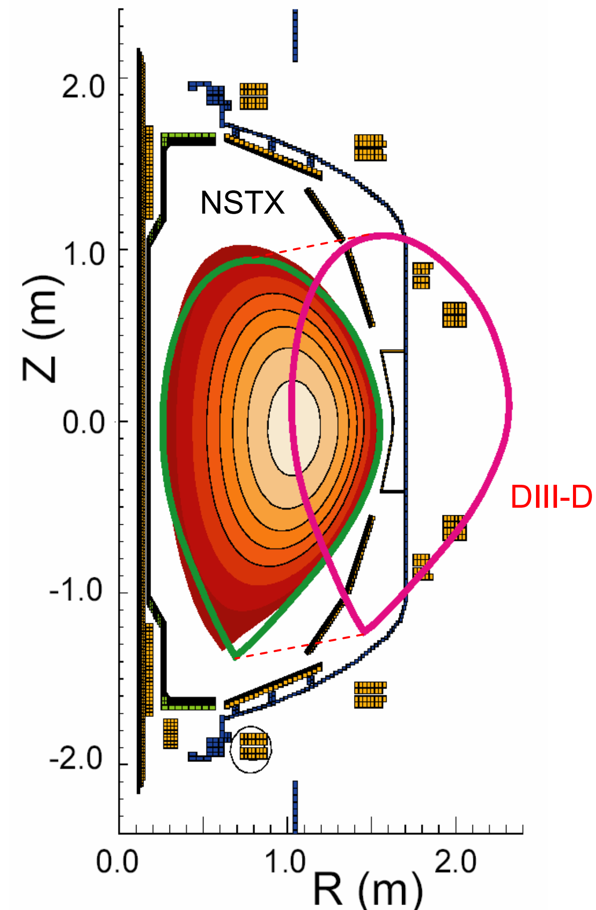


Collaborative Research with DIII-D and C-Mod is a Key Element of the NSTX program

Ongoing Coordinated Research:

- **MHD: active mode control; fast ion modes**
  - DIII-D: physics of different $V_{Alfvén}$
- **Transport: core confinement & H-mode pedestal**
  - DIII-D: similarity studies, with MAST researchers
- **Solenoid-free startup**
  - DIII-D: PF-only startup tests, with JT-60U researchers
- **EBW: mode conversion and deposition – off-axis current drive & NTM stabilization**
  - DIII-D: Operate with overdense conditions, using 110 GHz gyrotrons & PPPL launcher?
  - Modeling study underway.
- **Core measurement, SOL/edge transport & turbulence**
  - C-Mod: Fast camera gas puff imaging studies
  - C-Mod: X-ray crystal spectrometer for T_i & T_e

Various Plasma Shapes Available for Physics Comparison



NSTX National Team Contributes to Fusion Energy Sciences Along A Broad Front

- NSTX research addresses key scientific issues and supports
  - Fundamental understanding
  - Configuration optimization
  - Burning plasmas through ITPA
  - Physics database toward future ST's
- FY04-06 research aims to advance control and high β physics, the near-term goal of the NSTX 5-Year Research Plan
  - How does turbulence cause heat, particle & momentum losses?
  - What limits maximum plasma pressure & bootstrap current?
  - How do electromagnetic waves interact with plasma?
  - How is plasma magnetic flux generated?
  - How to interface fusion plasmas to surrounding materials?
  - How much external control vs. self-organization is needed?
- Additional investment in EBW and particle control required to develop high β long pulse discharges
- Strong contributions to ITPA, and broad collaborations worldwide